TOWN OF LOS ALTOS HILLS

SEWER FLOW MONITORING AND INFLOW / INFILTRATION STUDY

Prepared for: Town of Los Altos Hills
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Los Altos Hills, CA 94022

Date: November 2016

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V&A Project No. 14-0422

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Appendix A. Flow Monitoring Sites: Data, Graphs, Information

ABBREVIATIONS, TERMS AND DEFINITIONS USED IN THIS REPORT

Table i. Abbreviations

Abbreviation	Term
ADWF	average dry weather flow
CCTV	closed-circuit television
CDEC	California Data Exchange Center
CIP	capital improvement plan
CO	carbon monoxide
CWOP	Citizen Weather Observing Program
d/D	depth/diameter ratio
FM	flow monitor
gpd	gallons per day
gpm	gallons per minute
GWI	groundwater infiltration
H_2S	hydrogen sulfide
I/I	inflow and infiltration
IDW	inverse distance weighting
LEL	lower explosive limit
mgd	million gallons per day
NOAA	National Oceanic and Atmospheric Administration
Q	flow rate
RDI/I	rainfall-dependent infiltration and inflow
RG	rain gauge
SSO	sanitary sewer overflow
WEF	Water Environment Federation
WRCC	Western Regional Climate Center

Table ii. Terms and Definitions

Term	Definition
Average dry weather flow (ADWF)	Average flow rate or pattern from days without noticeable inflow or infiltration response. ADWF usage patterns for weekdays and weekends differ and must be computed separately. ADWF is expressed as a numeric average and includes the influence of normal groundwater infiltration (not related to a rain event).
Basin	Sanitary sewer collection system upstream of a given location (often a flow meter), including all pipelines, inlets, and appurtenances. Also refers to the ground surface area near and enclosed by pipelines. A basin may refer to the entire collection system upstream from a flow meter or exclude separately monitored basins upstream.
Depth/diameter (*d/D*) ratio	Depth of water in a pipe as a fraction of the pipe's diameter. A measure of fullness of the pipe used in capacity analysis.
Design storm	A theoretical storm event of a given duration and intensity that aligns with historical frequency records of rainfall events. For example, a 10-year, 24-hour design storm is a storm event wherein the volume of rain that falls in a 24-hour period would historically occur once every 10 years. Design storm events are used to predict I/I response and are useful for modeling how a collection system will react to a given set of storm event scenarios.
Infiltration and inflow	Infiltration and inflow (I/I) rates are calculated by subtracting the ADWF flow curve from the instantaneous flow measurements taken during and after a storm event. Flow in excess of the baseline consists of inflow, rainfall-responsive infiltration, and rainfall-dependent infiltration. **Total I/I** is the total sum in gallons of additional flow attributable to a storm event.
Infiltration, *groundwater*	Groundwater infiltration (**GWI**) is groundwater that enters the collection system through pipe defects. GWI depends on the depth of the groundwater table above the pipelines as well as the percentage of the system that is submerged. The variation of groundwater levels and subsequent groundwater infiltration rates is seasonal by nature. On a day-to-day basis, groundwater infiltration rates are relatively steady and will not fluctuate greatly.
Infiltration, *rainfall-dependent*	Rainfall-dependent infiltration (**RDI**) is similar to groundwater infiltration but occurs as a result of storm water. The storm water percolates into the soil, submerges more of the pipe system, and enters through pipe defects. RDI is the slowest component of storm-related infiltration and inflow, beginning gradually and often lasting 24 hours or longer. The response time depends on the soil permeability and saturation levels.
Inflow	**Inflow** is defined as water discharged into the sewer system, including private sewer laterals, from **direct** connections such as downspouts, yard and area drains, holes in manhole covers, cross-connections from storm drains, or catch basins. Inflow creates a peak flow problem in the sewer system and often dictates the required capacity of downstream pipes and transport facilities to carry these peak instantaneous flows. Overflows are often attributable to high inflow rates.
Peaking factor	Ratio of peak measured flow to average dry weather flow. This ratio expresses the degree of fluctuation in flow rate over the monitoring period and is used in capacity analysis.
Surcharge	When the flow level is higher than the crown of the pipe, then the pipeline is said to be in a **surcharged** condition. The pipeline is surcharged when the *d/D* ratio is greater than 1.0.
Synthetic hydrograph	A set of algorithms has been developed to approximate the actual I/I hydrograph. The synthetic hydrograph is developed strictly using rainfall data and response parameters representing response time, recession coefficient and soil saturation.

ES EXECUTIVE SUMMARY

Scope and Purpose

V&A Consulting Engineers (V&A) has completed sanitary sewer flow monitoring and I/I analysis within the Town of Los Altos Hills (Town) collection system. Flow monitoring was performed over a 8-week period from February 1, 2016 to March 27, 2016 at 12 open-channel flow monitoring locations. There were three general purposes of this study. Additionally, V&A installed one rain gauge to measure rainfall throughout the monitoring period. There were three general purposes of this study.

1. Establish the baseline sanitary sewer flows at the flow monitoring sites.
2. Estimate available sewer capacity.
3. Isolate I/I response and perform preliminary I/I analyses.

Monitoring Sites

The flow monitoring sites were selected and approved by the Town with the assistance of V.W. Housen & Associates and are listed in Table ES-1 and shown in Figure ES-1.

Table ES-1. List of Monitoring Sites

Monitoring Site	Manhole ID	Measured Pipe Diameter (in)	Location
Site 1	AMH1008	12	South end of Old Page Mill Rd. at Page Mill Rd.
Site 2	CMH1016	6	Foothill Expressway, 300 feet south of Arastradero Rd.
Site 3	BMH1038	10	Intersection of Arastradero Rd. and Hillview Ave.
Site 4	EMH1115	10	Fremont Rd. 600 feet north of intersection of Concepcion Rd and Fremont Rd.
Site 5	EMH1003	7.75	Elena Rd., just west of Highway 280 overpass
Site 6	FMH1006	8	Fremont Rd., 80 feet southeast of W. Edith Ave.
Site 7A	LMH1115	8	In parking lot of Foothill College, 450 feet east of intersection of Moody Rd and Elena Rd.

Monitoring Site	Manhole ID	Measured Pipe Diameter (in)	Location
Site 7B	LMH1067	6	O'Keefe Ln, 240 feet east of Dover Ct.
Site 7C	Line End 07	12	Northeast-bound El Monte Rd., 130 feet northeast of Summerhill Ave.
Site 8	LMH1126	9.5	El Monte Rd., 225 feet south of intersection of Moody Rd and Elena Rd.
Site 9	QMH1058	12	Intersection of Magdalena Ave and Summerhill Ave.
Site 10	QMH1121	8	South end of Westbrook Ave.

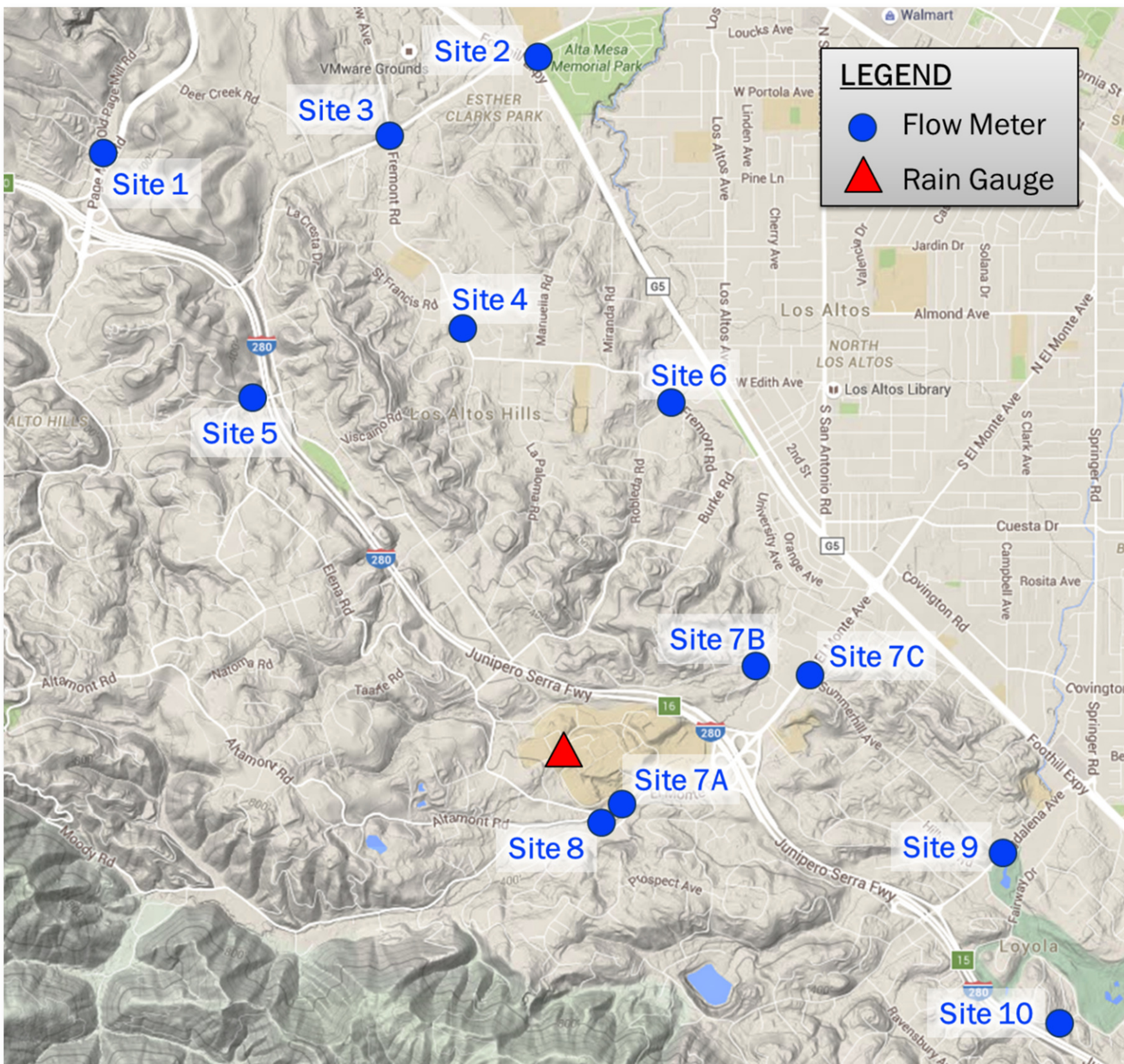


Figure ES-1. Map of Flow Monitoring Sites

Rainfall Monitoring

The March 4 - 8 rainfall was the largest rainfall event over the flow monitoring period and was classified as a 2-Year, 12-Hour storm event. The 10 days of rainfall from March 4 – 14 was classified as a 2-Year, 10-Day storm event. The combined March 4 - 8 and the March 10 - 14 storms caused the greatest I/I response in the Town collection system; these two storms were merged into one rainfall event for the I/I analyses conducted in this report.

Flow Monitoring and Capacity Results

Peak measured flows and the consequent hydraulic grade line data (flow depths) are important to understand the capacity limitations of a collection system. The following capacity analyses terms are defined as follows:

- **d/D Ratio:** The d/D ratio is the peak measured depth of flow (d) divided by the pipe diameter (D). Standards for d/D ratio vary from agency to agency, but typically range between d/D ≤ 0.5 and d/D ≤ 0.75.
- **Peaking Factor:** Peaking factor is defined as the peak measured flow divided by the average dry weather flow (ADWF). A peaking factor threshold value of 3.0 is commonly used for sanitary sewer design of new pipe; however, it is noted that this value is variable and subject to attenuation and the size of the upstream collector area. The Town should follow its own standards and criteria when examining peaking factors.

Table ES-2 summarizes the peak recorded flows, levels, *d/D* ratios, and peaking factors per site during the flow monitoring period. Results of note have been shaded in RED. Capacity analysis data is presented on a site-by-site basis and represents the hydraulic conditions only at the site locations; hydraulic conditions in other areas of the collection system will differ.

Table ES-2. Capacity Analysis Summary

Metering Site	ADWF (mgd)	Peak Measured Flow (mgd)	Peaking Factor	Pipe Diameter, *D* (in)	Max Depth, *d* (in)	*Max d/D* Ratio	Surcharge above Pipe Crown (ft)
Site 1	0.124	0.933	7.5	12	4.56	0.38	-
Site 2	0.026	0.146	5.6	6	4.20	0.70	-
Site 3	0.109	0.657	6.0	10	3.78	0.38	-
Site 4	0.036	0.358	10.0	10	5.28	0.53	-
Site 5	0.004	0.042	9.9	7.75	1.03	0.13	-
Site 6	0.006	0.048	8.1	8	1.81	0.23	-
Site 7A	0.103	0.503	4.9	8	3.32	0.42	-
Site 7B	0.007	0.026	3.6	6	1.24	0.21	-
Site 7C	0.143	0.694	4.0	12	3.85	0.32	-

Metering Site	ADWF (mgd)	Peak Measured Flow (mgd)	Peaking Factor	Pipe Diameter, *D* (in)	Max Depth, *d* (in)	*Max d/D* Ratio	Surcharge above Pipe Crown (ft)
Site 8	0.055	0.319	5.8	9.5	2.37	0.25	-
Site 9	0.071	0.502	7.1	12	5.31	0.44	-
Site 10	0.025	0.120	4.8	8	2.13	0.27	-

The following capacity analysis results are noted:

- **d/D Ratio:** None of the sites had a maximum *d/D* ratio that exceeded a d/D value of 0.75. None of the sites experienced surcharging during this study.
- **Peaking Factor:** All of the metering sites had peaking factors that exceeded typical design threshold limits for new pipe design. The peak flows for all sites were rainfall-related.

Infiltration and Inflow Analysis

Table ES-3 summarizes the flow monitoring and I/I results for the flow monitoring sites that were monitored during this study. I/I results presented are for the March 4 – 14, 2016 rainfall event. Results for each I/I component are expressed as a ratio to ADWF. Please refer to the *I/I Methods* section for more information on inflow and infiltration analysis methods.

Table ES-3. I/I Analysis Summary

Metering Site	ADWF (mgd)	Peak I/I Rate (mgd)	Combined I/I (gallons)	Peak I/I per ADWF	RDI per ADWF	Combined I/I per ADWF	Evidence of GWI?
Site 1	0.124	0.782	4,103,000	6.3	2.0	2.0	No
Site 2	0.026	0.116	348,000	4.4	0.6	0.8	Yes
Site 3	0.109	0.561	2,251,000	5.1	1.2	1.2	No
Site 4	0.036	0.340	1,581,000	9.5	2.2	2.6	No
Site 5	0.004	0.036	127,000	8.5	2.4	1.8	No
Site 6	0.006	0.041	192,000	7.0	2.6	1.9	Yes
Site 7A	0.103	0.370	1,102,000	3.6	0.6	0.6	Yes
Site 7B	0.007	0.018	34,000	2.4	0.0	0.3	Yes
Site 7C	0.143	0.628	2,148,000	4.4	0.8	0.9	No
Site 8	0.055	0.217	634,000	4.1	0.6	0.7	Yes
Site 9	0.071	0.410	1,281,000	5.8	1.0	1.1	No
Site 10	0.025	0.085	362,000	3.4	1.0	0.9	Yes

I/I Investigation and Reduction

For this study, it is not V&A's intent to suggest the next course of action to be taken in regards to any CIP decisions regarding collection system capacity or RDI/I mitigation. The Town master planning consultant will determine the effect of the rainfall intensity on the RDI/I response within the collection system. V&A will not make any specific recommendations in this final report. However, it is noted that Sites 1, 4, 5 and 6 had the highest I/I ratios for inflow, rain dependent infiltration and total combined I/I.

These data and the interpretation of these data should be used per the discretion of the Town Engineer.

V&A presents the following general I/I reduction guidelines for I/I mitigation and reduction:

1. **Determine I/I Reduction Program:** The Town should examine its I/I reduction needs to determine a future I/I reduction program.
   a. If peak flows, sanitary sewer overflows, and pipeline capacity issues are of greater concern, then priority can be given to investigate and reduce sources of inflow within the basins with the greatest inflow problems.
   b. If total infiltration and general pipeline deterioration are of greater concern, then the program can be weighted to investigate and reduce sources of infiltration within the basins with the greatest infiltration problems.
2. **I/I Investigation Methods:** Potential I/I investigation methods include the following:
   a. Smoke testing
   b. Mini-basin flow monitoring
   c. Nighttime reconnaissance work to (1) investigate and determine direct point sources of inflow and (2) determine the areas and pipe reaches responsible for high levels of infiltration contribution.
3. **I/I Reduction Cost-Effectiveness Analysis:** The Town should conduct a study to determine which is more cost-effective: (1) locating the sources of inflow and infiltration and systematically rehabilitating or replacing the faulty pipelines or (2) continued treatment of the additional rainfall-dependent I/I flow.

1.0 INTRODUCTION

1.1 Scope and Purpose

V&A has completed sanitary sewer flow monitoring and inflow and infiltration (I/I) analysis within the Town of Los Altos Hills (Town). Flow monitoring and inflow and infiltration (I/I) analysis was performed over a 8-week period from February 1, 2016 to March 27, 2016 at 12 open-channel flow monitoring sites throughout the Town. Additionally, V&A installed one rain gauge to measure rainfall throughout the monitoring period.

There were three general purposes of this study.

1. Establish the baseline sanitary sewer flows at the flow monitoring sites.
2. Estimate available sewer capacity.
3. Isolate I/I response and perform I/I analysis.

1.2 Flow Monitoring Sites and Rain Gauge

Flow monitoring sites are the manholes where the flow monitors were placed. Capacity and flow rate information is presented in this report on a site-by-site basis. Maps, photographs and detailed descriptions of the individual flow monitoring sites are included in *Appendix A*.

Flow monitoring site data may include the flows of one or many drainage basins. To isolate a particular drainage basin, an addition or subtraction of flows may be required[1]. For this study, the following subtraction applies for measuring flow from Foothill College, located in the southern part of the study area:

- Foothill College flow = Meter 7C – Meter 7A – Meter 7B

Rain data was measured using a rain gauge installed by V&A at Foothill College Building 4400 on Perimeter Road.

Flow monitoring locations are listed in Table 1-1 below. The flow monitoring and rain gauge locations are shown in Figure 1-1.

[1] There is error inherent in flow monitoring. Adding and subtracting flows increases error on an additive basis. For example, if Site A has an error of ±10% and Site B has an error of ±10%, then the resulting flow when subtracting Site A from Site B would have an error of up to ±20%.

Table 1-1. List of Flow Monitoring Locations

Monitoring Site	Pipe Diameter (in)	Location
Site 1	12	South end of Old Page Mill Rd. at Page Mill Rd.
Site 2	6	Foothill Expressway, 300 feet south of Arastradero Rd.
Site 3	10	Intersection of Arastradero Rd. and Hillview Ave.
Site 4	10	Fremont Rd. 600 feet north of intersection of Concepcion Rd and Fremont Rd.
Site 5	7.75	Elena Rd., just west of Highway 280 overpass
Site 6	8	Fremont Rd., 80 feet southeast of W. Edith Ave.
Site 7A	8	Foothill College Parking Lot, 450 feet east of intersection of Moody Rd and Elena Rd.
Site 7B	6	O'Keefe Ln, 240 feet east of Dover Ct.
Site 7C	12	Northeast-bound El Monte Rd., 130 feet northeast of Summerhill Ave.
Site 8	9.75	El Monte Rd., 225 feet south of intersection of Moody Rd and Elena Rd.
Site 9	12	Intersection of Magdalena Ave and Summerhill Ave.
Site 10	8	South end of Westbrook Ave.

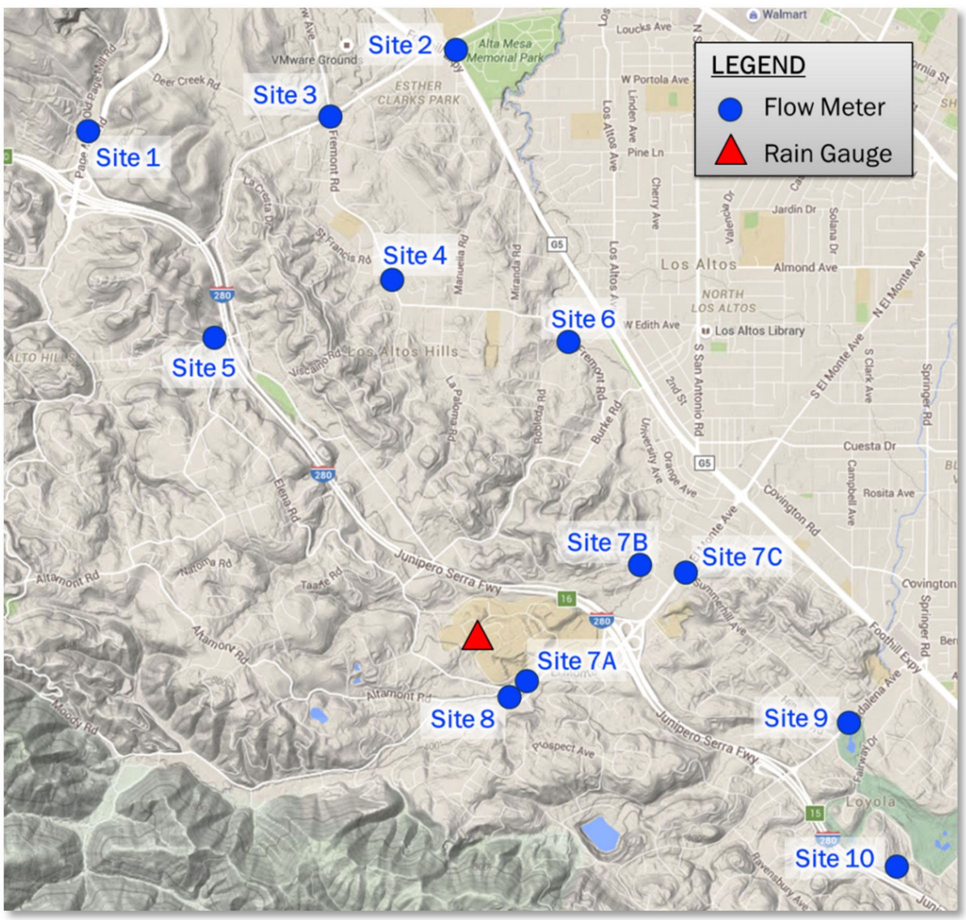


Figure 1-1. Map of Flow Monitoring Sites

2.0 METHODS AND PROCEDURES

2.1 Confined Space Entry

A confined space (Photo 2-1) is defined as any space that is large enough and so configured that a person can bodily enter and perform assigned work, has limited or restricted means for entry or exit and is not designed for continuous employee occupancy. In general, the atmosphere must be constantly monitored for sufficient levels of oxygen (19.5% to 23.5%), and the presence of hydrogen sulfide (H_2S) gas, carbon monoxide (CO) gas, and lower explosive limit (LEL) levels. A typical confined space entry crew has members with OSHA-defined responsibilities of Entrant, Attendant and Supervisor. The Entrant is the individual performing the work. He or she is equipped with the necessary personal protective equipment needed to perform the job safely, including a personal four-gas monitor (Photo 2-2). If it is not possible to maintain line-of-sight with the Entrant, then more Entrants are required until line-of-sight can be maintained. The Attendant is responsible for maintaining contact with the Entrants to monitor the atmosphere using another four-gas monitor and maintaining records of all Entrants, if there is more than one. The Supervisor is responsible for developing the safe work plan for the job at hand prior to entering.

Photo 2-1. Confined Space Entry

Photo 2-2. Typical Personal Four-Gas Monitor

2.2 Flow Meter Installation

V&A installed eleven Isco 2150 area-velocity flow meters for temporary metering within the collection system. One Flo-Dar meter was installed at Site 10. Isco 2150 meters use submerged sensors with a pressure transducer to collect depth readings and an ultrasonic Doppler sensor to determine the average fluid velocity. The ultrasonic sensor emits high-frequency (500 kHz) sound waves, which are reflected by air bubbles and suspended particles in the flow. The sensor receives the reflected signal and determines the Doppler frequency shift, which indicates the estimated average flow velocity. The sensor is typically mounted at a manhole inlet to take advantage of smoother upstream flow conditions. The sensor may be offset to one side to lessen the chances of fouling and sedimentation where these problems are expected to occur. Manual level and velocity measurements were taken during installation of the flow meters and again when they were removed and compared to simultaneous level and velocity readings from the flow meters to ensure proper calibration and accuracy. Figure 2-1 shows a typical installation for a flow meter with a submerged sensor.

A Flo-Dar flow meter is a non-contact flow meter that uses radar to measure velocity and a down-looking ultrasonic sensor to measure depth. Figure 2-2 illustrates a typical Flo-Dar installation.

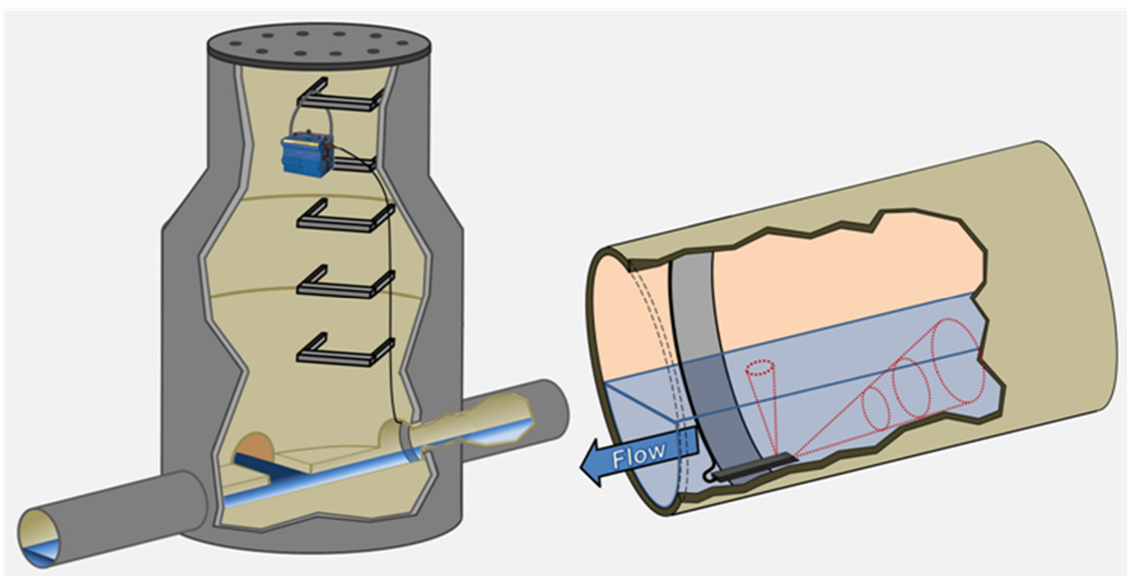


Figure 2-1. Typical Installation for Flow Meter with Submerged Sensor

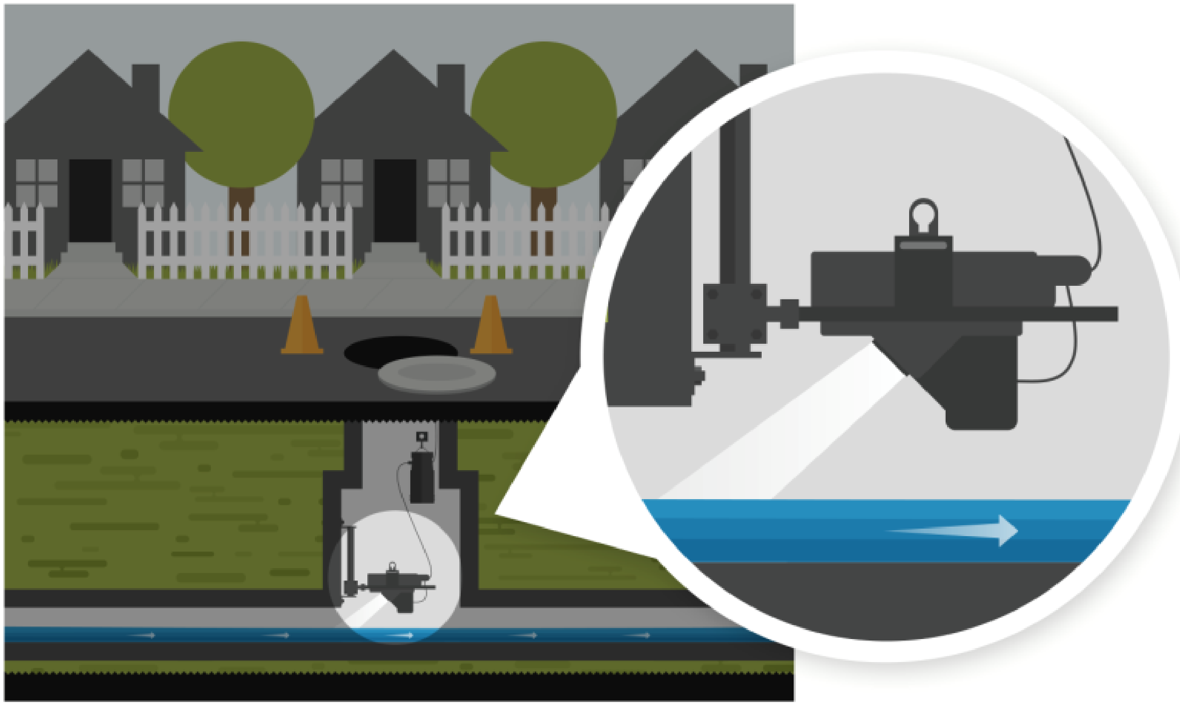


Figure 2-2. Typical Flo-Dar Flow Meter Installation

2.3 Flow Calculation

Data retrieved from the flow meter was placed into a spreadsheet program for analysis. Data analysis includes data comparison to field calibration measurements, as well as necessary geometric adjustments as required for sediment (sediment reduces the pipe's wetted cross-sectional area available to carry flow). Area-velocity flow metering uses the continuity equation,

$$Q = v \cdot A = v \cdot (A_T - A_S)$$

where Q : volume flow rate
v: average velocity as determined by the ultrasonic sensor
A: cross-sectional area available to carry flow
A_T: total cross-sectional area with both wastewater and sediment
A_S: cross-sectional area of sediment.

For circular pipe,

$$A_T = \left[\frac{D^2}{4}\cos^{-1}\left(1-\frac{2d_W}{D}\right)\right]-\left[\left(\frac{D}{2}-d_W\right)\left(\frac{D}{2}\right)\sin\left(\cos^{-1}\left(1-\frac{2d_W}{D}\right)\right)\right]$$

$$A_S = \left[\frac{D^2}{4}\cos^{-1}\left(1-\frac{2d_S}{D}\right)\right]-\left[\left(\frac{D}{2}-d_S\right)\left(\frac{D}{2}\right)\sin\left(\cos^{-1}\left(1-\frac{2d_S}{D}\right)\right)\right]$$

where d_W: distance between wastewater level and pipe invert
d_S: depth of sediment
D: pipe Diameter

2.4 Average Dry Weather Flow Determination

For this study, four distinct average dry weather flow curves were established for each site location:

- Mondays – Thursdays
- Fridays
- Saturdays
- Sundays

Flows for many sites differ on Friday evenings compared to Mondays through Thursdays. Starting around 7 pm, the flows are often decreased (compared to Monday through Thursday). Similarly, flow patterns for Saturday and Sunday each have unique evening flow patterns. This type of differentiation can be important when determining I/I response, especially if a rain event occurs on a Friday, Saturday or Sunday evening.

Figure 2-3 illustrates a sample of varying flow patterns within a typical week dry week.

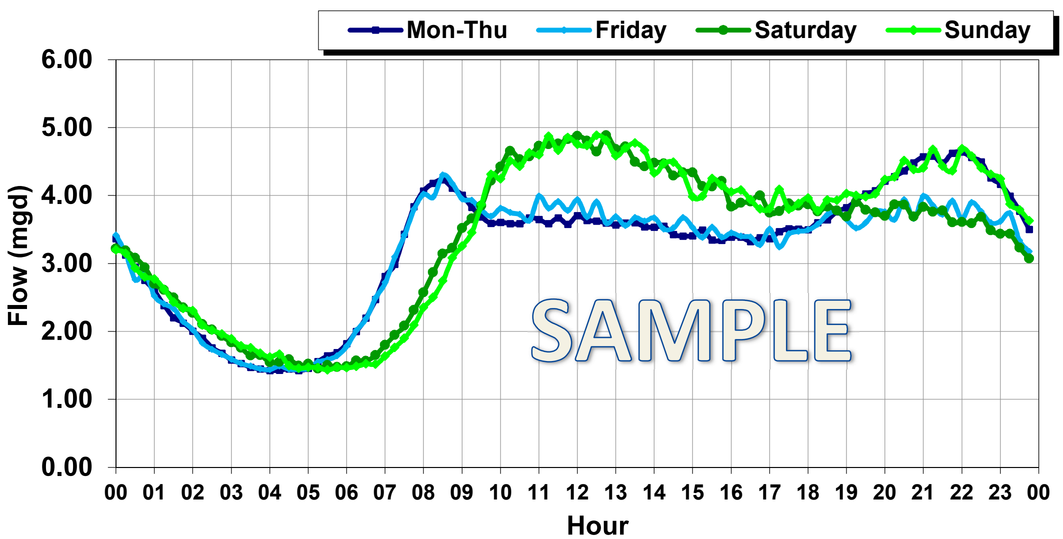


Figure 2-3. Sample ADWF Diurnal Flow Patterns

ADWF curves were generally derived from two sets of "Dry Days" when RDI had the least impact on the baseline flow. The first set of dry days occurred between February 1 and February 12, 2016, while the second set of dry days occurred between February 20 and March 3, 2016.

The overall average dry weather flow (ADWF) was calculated per the following equation:

$$ADWF = \left(ADWF_{Mon-Thu} \times \frac{4}{7}\right) + \left(ADWF_{Fri} \times \frac{1}{7}\right) + \left(ADWF_{Sat} \times \frac{1}{7}\right) + \left(ADWF_{Sun} \times \frac{1}{7}\right),$$

2.5 Flow Attenuation

Flow attenuation in a sewer collection system is the natural process of the reduction of the peak flow rate through redistribution of the same volume of flow over a longer period of time. This occurs as a result of friction (resistance), internal storage and diffusion along the sewer pipes. Fluids are constantly working towards equilibrium. For example, a volume of fluid poured into a static vessel with no outside turbulence will eventually stabilize to a static state, with a smooth fluid surface without peaks and valleys. Attenuation within a sanitary sewer collection system is based upon this concept. A flow profile with a strong peak will tend to stabilize towards equilibrium, as shown in Figure 2-4.

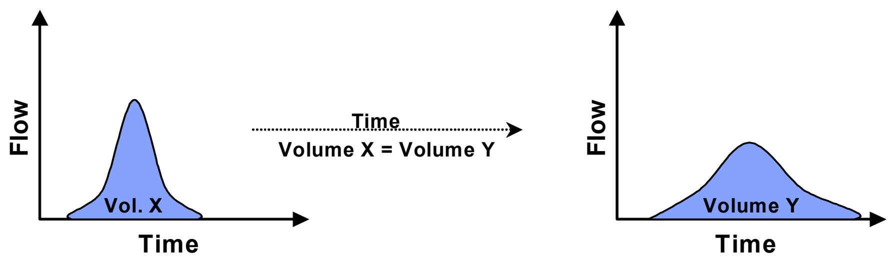


Figure 2-4. Attenuation Illustration

Within a sanitary sewer collection system, each individual basin will have a specific flow profile. As the flows from the basins combine within the trunk sewer lines, the peaks from each basin will (a) not necessarily coincide at the same time, and (b) due to the length and time of travel through the trunk sewers, peak flows will attenuate prior to reaching the treatment facility. The sum of the peak flows of the individual basins within a collection system will usually be greater than the peak flows observed at the treatment facility.

2.6 Inflow / Infiltration Analysis: Definitions and Identification

Inflow and infiltration (I/I) consists of storm water and groundwater that enter the sewer system through pipe defects and improper storm drainage connections and is defined as follows:

2.6.1 Definition and Typical Sources

- **Inflow:** Storm water inflow is defined as water discharged into the sewer system, including private sewer laterals, from direct connections such as downspouts, yard and area drains, holes in manhole covers, cross-connections from storm drains, or catch basins.
- **Infiltration:** Infiltration is defined as water entering the sanitary sewer system through defects in pipes, pipe joints, and manhole walls, which may include cracks, offset joints, root intrusion points, and broken pipes.

Figure 2-5 illustrates the possible sources and components of I/I.

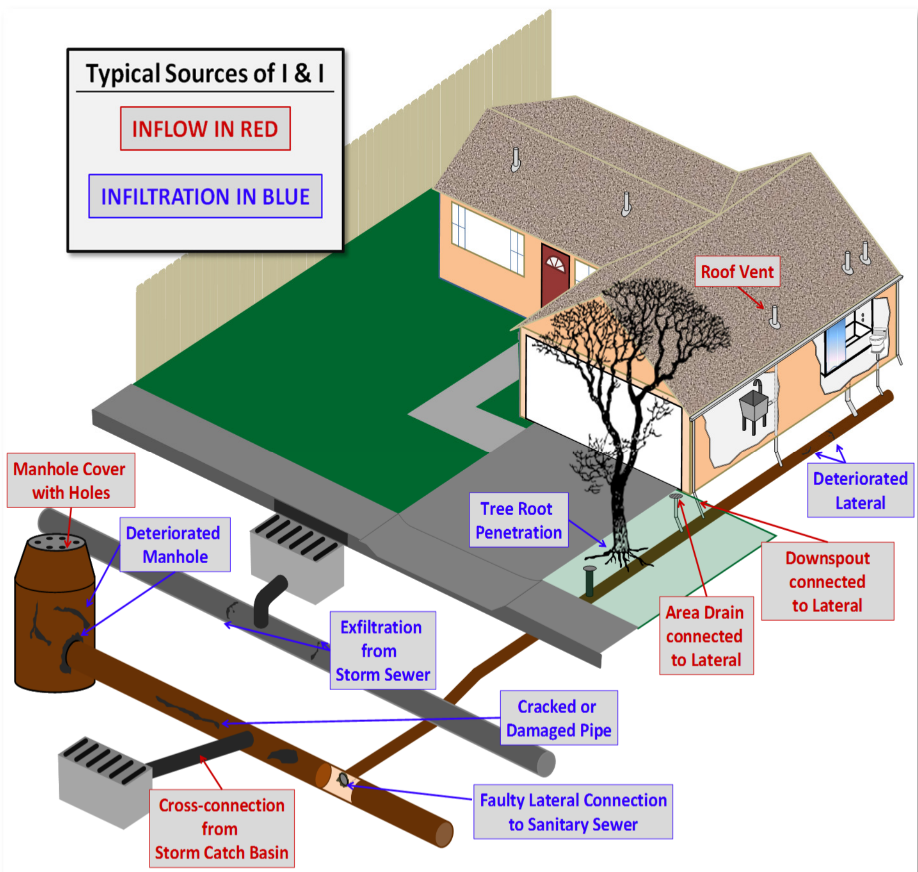


Figure 2-5. Typical Sources of Infiltration and Inflow

2.6.2 Infiltration Components

Infiltration can be further subdivided into components as follows:

- **Groundwater Infiltration:** Groundwater infiltration depends on the depth of the groundwater table above the pipelines as well as the percentage of the system submerged. The variation of groundwater levels and subsequent groundwater infiltration rates is seasonal by nature. On a day-to-day basis, groundwater infiltration rates are relatively steady and will not fluctuate greatly.
- **Rainfall-Dependent Infiltration:** This component occurs as a result of storm water and enters the sewer system through pipe defects, as with groundwater infiltration. The storm water first percolates directly into the soil and then migrates to an infiltration point. Typically, the time of concentration for rainfall-related infiltration may be 24 hours or longer, but this depends on the soil permeability and saturation levels.
- **Rainfall-Responsive Infiltration** is storm water which enters the collection system indirectly through pipe defects, but normally in sewers constructed close to the ground surface such as private laterals. Rainfall-responsive infiltration is independent of the groundwater table and reaches defective sewers via the pipe trench in which the sewer is constructed, particularly if the pipe is placed in impermeable soil and bedded and backfilled with a granular material. In this case, the pipe trench serves as a conduit similar to a French drain, conveying storm drainage to defective joints and other openings in the system. This type of infiltration can have a quick response and graphically can look very similar to inflow.

2.6.3 Impact and Cost of Source Detection and Removal

- **Inflow:**
  - **Impact:** This component of I/I creates a peak flow problem in the sewer system and often dictates the required capacity of downstream pipes and transport facilities to carry these peak instantaneous flows. Because the response and magnitude of inflow is tied closely to the intensity of the storm event, the short-term peak instantaneous flows may result in surcharging and overflows within a collection system. Severe inflow may result in sewage dilution, resulting in upsetting the biological treatment (secondary treatment) at the treatment facility.
  - **Cost of Source Identification and Removal:** Inflow locations are usually less difficult to find and less expensive to correct. These sources include direct and indirect cross-connections with storm drainage systems, roof downspouts, and various types of surface drains. Generally, the costs to identify and remove sources of inflow are low compared to potential benefits to public health and safety or the costs of building new facilities to convey and treat the resulting peak flows.
- **Infiltration:**
  - **Impact:** Infiltration typically creates long-term annual volumetric problems. The major impact is the cost of pumping and treating the additional volume of water, and of paying for treatment (for municipalities that are billed strictly on flow volume).

- **Cost of Source Detection and Removal:** Infiltration sources are usually harder to find and more expensive to correct than inflow sources. Infiltration sources include defects in deteriorated sewer pipes or manholes that may be widespread throughout a sanitary sewer system.

2.6.4 Graphical Identification of I/I

Inflow is usually recognized graphically by large-magnitude, short-duration spikes immediately following a rain event. Infiltration is often recognized graphically by a gradual increase in flow after a wet-weather event. The increased flow typically sustains for a period after rainfall has stopped and then gradually drops off as soils become less saturated and as groundwater levels recede to normal levels. Realtime flows were plotted against ADWF to analyze the I/I response to rainfall events. Figure 2-6 illustrates a sample of how this analysis is conducted and some of the measurements that are used to distinguish infiltration and inflow. Similar graphs were generated for the individual flow monitoring sites and can be found in *Appendix A*.

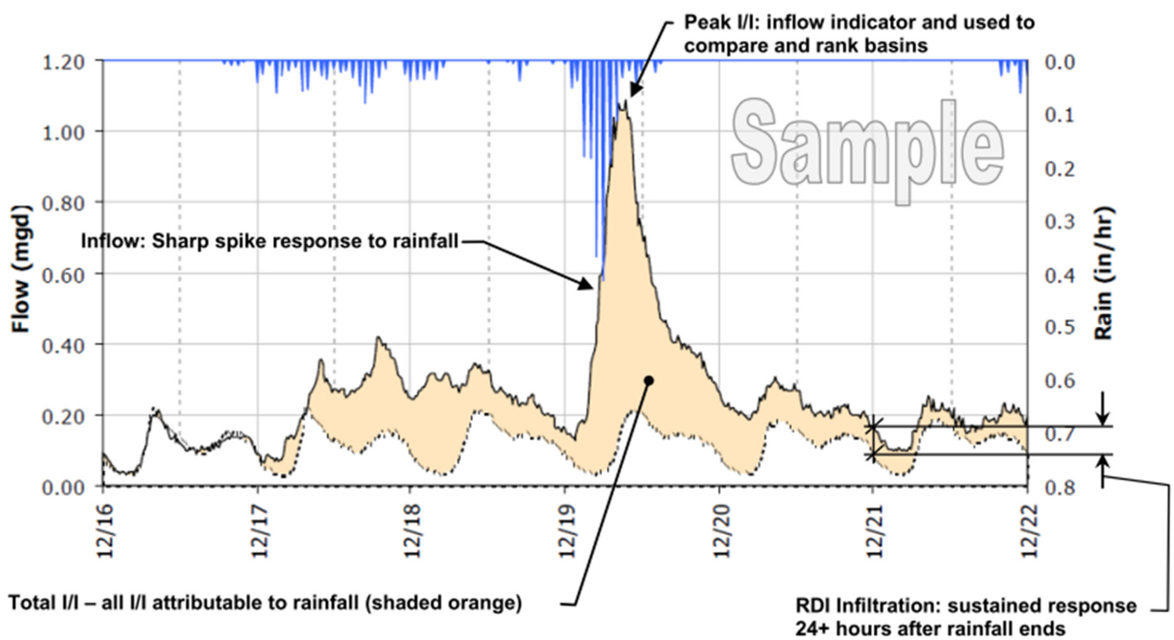


Figure 2-6. Sample Infiltration and Inflow Isolation Graph

Figure 2-7 shows sample graphs indicating the typical graphical response patterns for inflow and infiltration in a more detailed version.

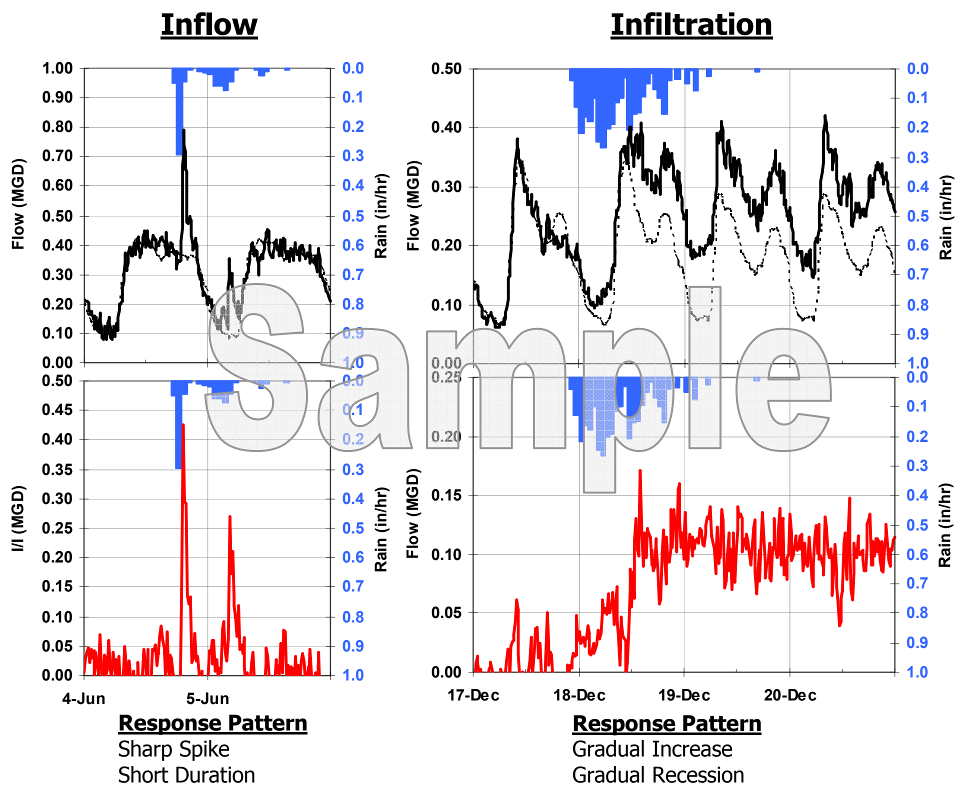


Figure 2-7. Inflow and Infiltration: Graphical Response Patterns

2.6.5 Analysis Metrics

After differentiating I/I flows from ADWF flows, various calculations can be made to determine which I/I component (inflow or infiltration) is more prevalent at a particular site and to compare the relative magnitudes of the I/I components between drainage basins and between storm events:

Inflow – Peak I/I Flow Rate: Inflow is characterized by sharp, direct spikes occurring during a rainfall event. Peak I/I rates are used for inflow analysis[2].

Groundwater Infiltration: GWI analysis is conducted by looking at minimum dry weather flow to average dry weather flow ratios and comparing them to established standards to quantify the rate of excess groundwater infiltration.

Rainfall-Dependent Infiltration: Infiltration occurring after the conclusion of a storm event is classified as rainfall-dependent infiltration (RDI). RDI Analysis is conducted by looking at the infiltration rates at set periods after the conclusion of a storm event. Depending on the particular collection system and the time required for flows to return to ADWF levels, different set periods may

[2] I/I flow rate is the real time flow less the estimated average dry weather flow rate. It is an estimate of flows attributable to rainfall. By using peak measured flow rates (inclusive of ADWF), the I/I flow rate would be skewed higher or lower depending on whether the storm event I/I response occurs during low-flow or high-flow hours.

be examined to determine the basins with the greatest or most sustained rainfall-dependent infiltration rates.

Total Infiltration: The total inflow and infiltration is measured in gallons per site and per storm event. Because it is based on total I/I volume, it is an indicator of combined inflow and infiltration and is used to identify the overall volumetric influence of I/I within the monitoring basin.

2.6.6 Normalization Methods

There are three ways to *normalize* the I/I analysis metrics for an "apples-to-apples" comparison amongst the different drainage basins:

- **per ADWF:** The metric is divided by the established average dry weather flow rate and typically expressed as a ratio. *Peaking Factor*s are examples of using ADWF to normalize data from different sites.
- **per IDM:** The metric is divided by length of pipe (IDM [inch-diameter mile]) contained within the upstream basin. Final units typically are gallons per day (gpd) per IDM.
- **per ACRE:** The metric is divided by the acreage of the upstream basin. Final units typically are gallons per day (gpd) per ACRE.

The infiltration and inflow indicators were normalized by the per-ADWF method only in this report.

3.0 RAINFALL RESULTS

3.1 Rainfall Monitoring

There were three main rainfall events that occurred over the course of the flow monitoring period, as summarized in Table 3-1 and illustrated in Figure 3-1. The combined March 4 - 8 and the March 10 - 14 storms caused the greatest I/I response in the Town collection system; these two storms were merged into one rainfall event for I/I analyses discussed later is this report.

Table 3-1. Rainfall Events

Rainfall Event	Foothill College (in)
February 17 – 18, 2016	1.27
March 4 – 8, 2016	4.12
March 10 – 14, 2016	2.50
Total over Monitoring Period	*8.35*

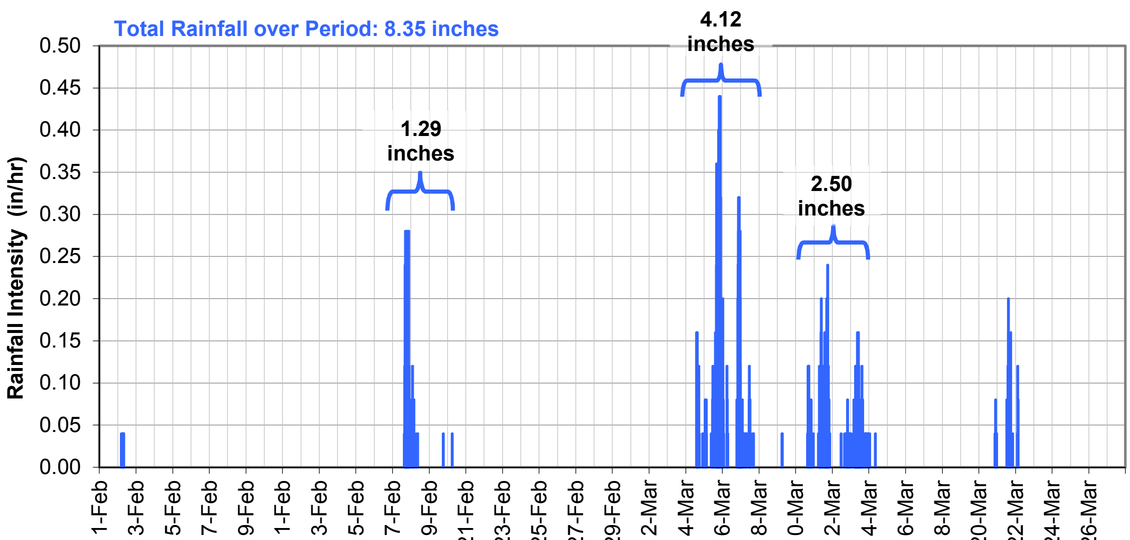


Figure 3-1. Rainfall Activity over Flow Monitoring Period at the Foothill College Rain Gauge

Figure 3-2 shows the rain accumulation plot of the period rainfall, as well as the historical average rainfall[3] in the Town during this project duration. Rainfall totals for Los Altos Hills were about 73% of historical average levels during this time period.

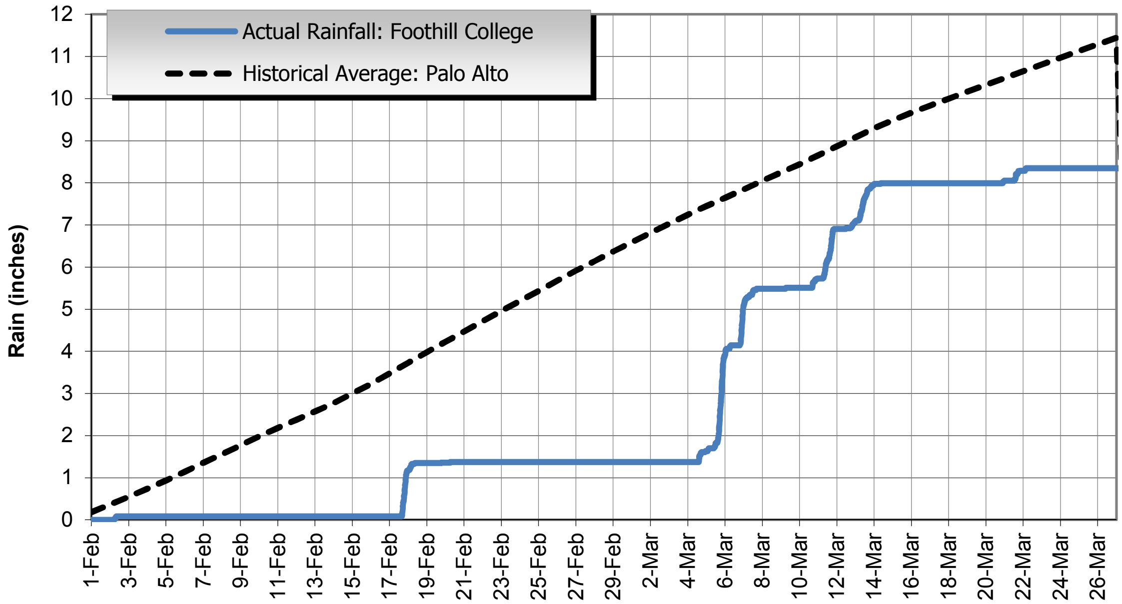


Figure 3-2. Accumulated Precipitation Monitored from Different Locations

The rainfall data from the Foothill College Rain Gauge was the only rain data used for this study. The following items are noted in regards to the analyses of this report:

- The Town collection system is expansive and has varying topographies. Therefore, the rainfall volumes and intensities within the individual flow monitoring basins will differ, possibly quite substantially.
- Several calculations within this report (such as peaking factors, peak flow rates and ratios to ADWF, etc.) are a function of the volume and intensity of rainfall. These calculations are also a function of the meter tributary area and flow attenuation within the system, which were also not known for this study.
- The reader is cautioned; the comparative analyses presented in the report are presented with acknowledgement of these unknowns.

[3] Historical data taken from the WRCC (Station 46646 in Palo Alto and Station 49792 in Woodside, triangulated and topographically weighted): http://www.wrcc.dri.edu/summary/climsmnca.html

3.2 Rainfall: Storm Event Classification

It is important to classify the relative size of the major storm event that occurs over the course of a flow monitoring period[4]. Storm events are classified by intensity and duration. Based on historical data, frequency contour maps for storm events of given intensity and duration have been developed by the National Oceanic and Atmospheric Administration (NOAA) for all areas within the continental United States. For example, the NOAA Rainfall Frequency Atlas[5] classifies a 10-year, 24-hour storm event at the Foothill College Rain Gauge location as 4.01 inches (Figure 3-3). This means that in any given year, at this specific location, there is a 10% chance that 4.01 inches of rain will fall in any 24-hour period.

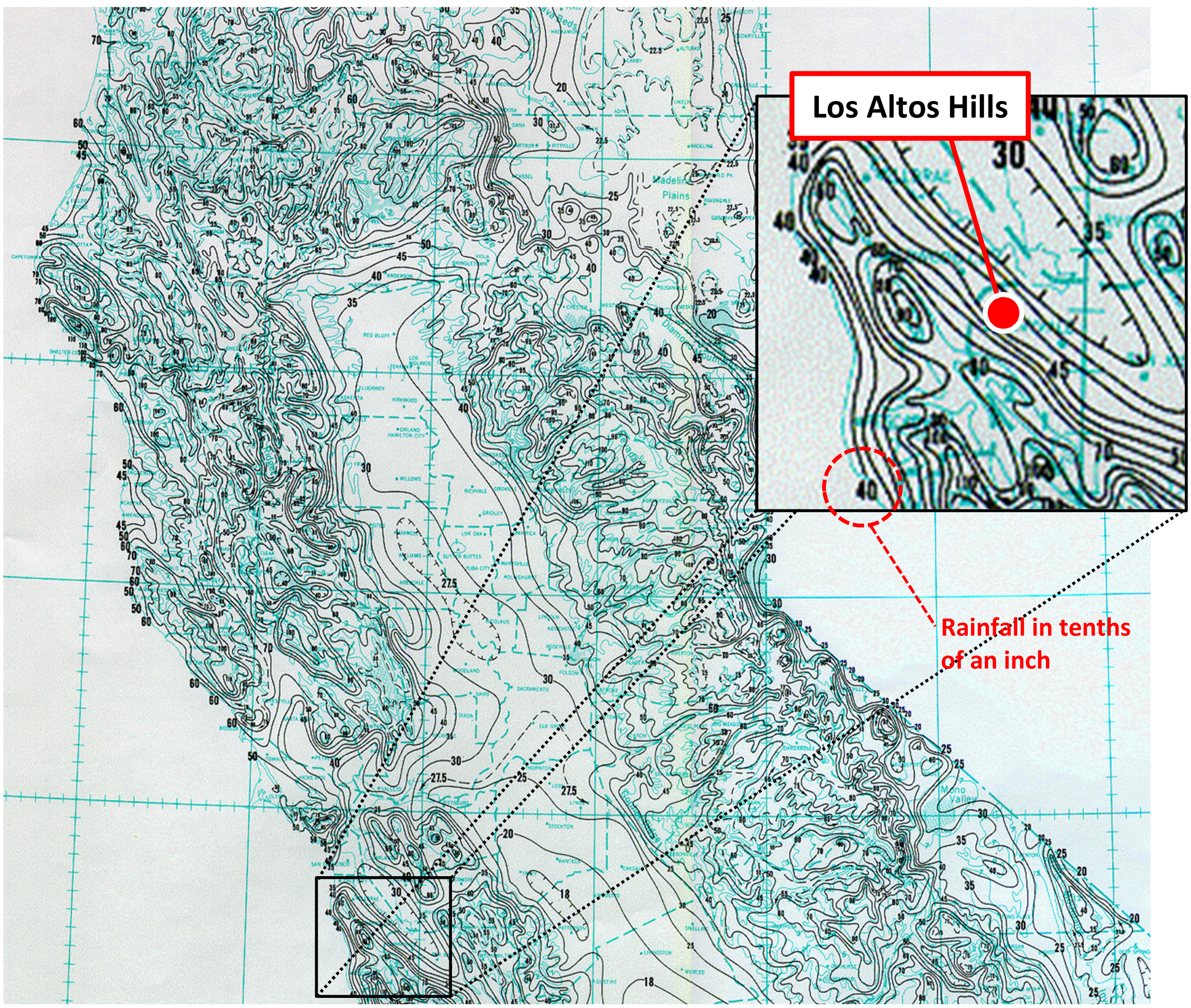


Figure 3-3. NOAA Northern California Rainfall Frequency Map

[4] Sanitary sewers are often designed to withstand I/I contribution to sanitary flows for specific-sized "design" storm events.
[5] A Atlas 14, Volume 6, Version 2 California ftp://hdsc.nws.noaa.gov/pub/hdsc/data/sw/ca10y24h.pdf

From the NOAA frequency maps, the rainfall densities for period durations ranging from 15 minutes to 60 days are known for rain events ranging from 1-year to 100-year intensities. These were plotted to develop a rain event frequency map specific to the Foothill College Rain Gauge. Superimposing the peak measured densities for all the rainfall events on the rain event frequency plot determines the classification of the storm event, as shown in Figure 3-4. Table 3-2 summarizes the classification of the rainfall events that occurred during the flow monitoring period.

Event 2 was the largest classified rainfall event over the flow monitoring period. It is also noted that the 10 days of rainfall from March 4 – 14 was classified as a 2-Year, 10-Day storm event.

Table 3-2. Classification of Rainfall Events at Foothill College Rain Gauge

Rainfall Event	Event Classification
February 17 – 18, 2016	< 1-Year
March 4 – 8, 2016	2-Year, 12-Hour
March 10 – 14, 2016	< 1-Year

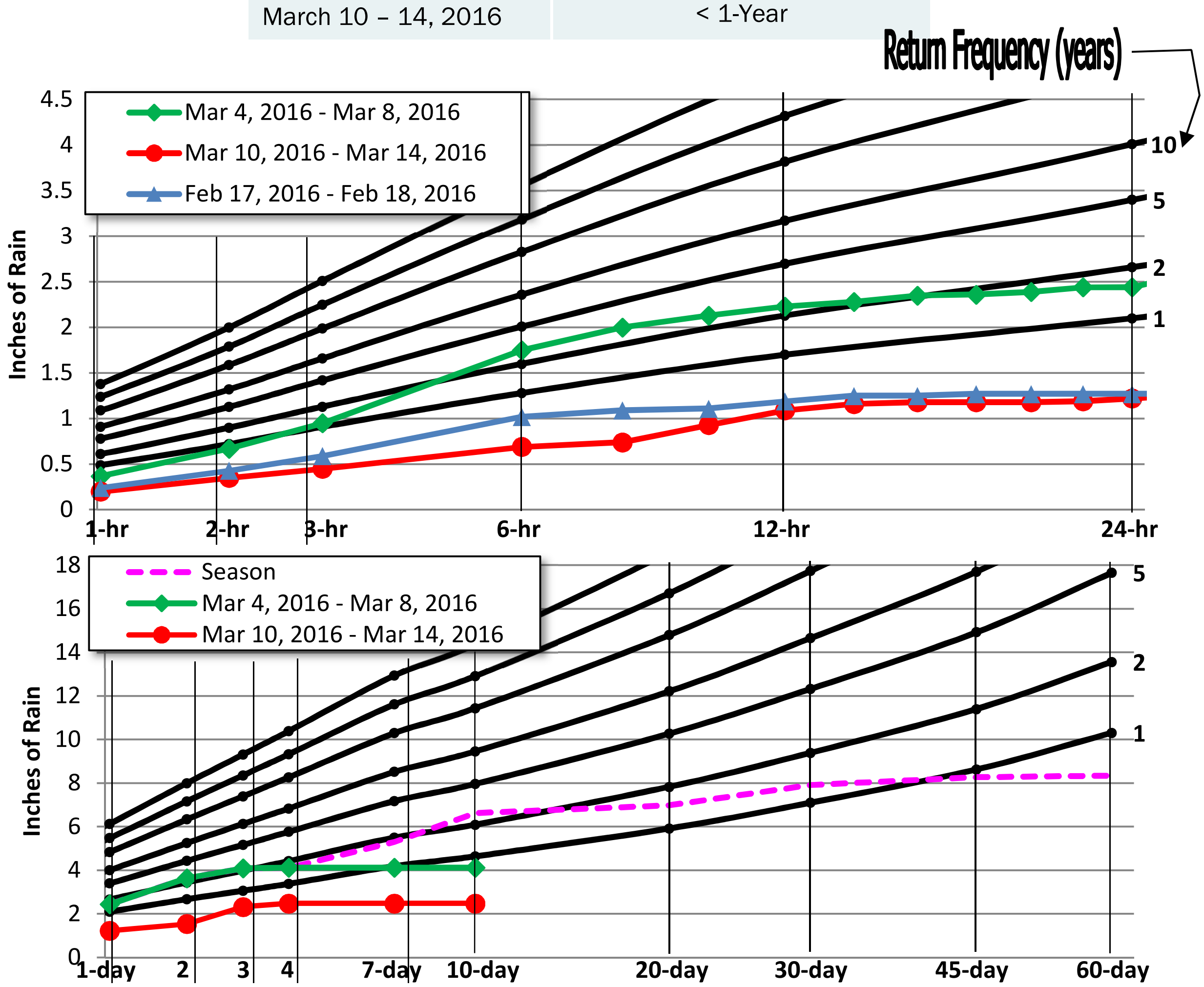


Figure 3-4. Storm Event Classification at the Foothill College Rain Gauge

4.0 Flow Monitoring Results

4.1 Average Flow Analysis

ADWF curves were established for the periods between February 1 and February 12, 2016 and February 20 and March 3, 2016 when RDI had the least impact on the baseline flow. Table 4-1 summarizes the dry weather flow data measured for this study. ADWF curves for each site can be found in *Appendix A*. Figure 4-1 shows a schematic diagram of the average dry weather flows and flow levels.

Table 4-1. Dry Weather Flow Summary

Monitoring Site	Sedimentation (inches)	Monday-Thursday ADWF (mgd)	Friday ADWF (mgd)	Saturday ADWF (mgd)	Sunday ADWF (mgd)	Overall ADWF (mgd)
Site 1	none	0.121	0.121	0.132	0.128	0.124
Site 2	0.4"	0.026	0.028	0.025	0.026	0.026
Site 3	none	0.111	0.113	0.107	0.101	0.109
Site 4	none	0.036	0.037	0.035	0.035	0.036
Site 5	none	0.004	0.004	0.003	0.004	0.004
Site 6	none	0.006	0.007	0.005	0.007	0.006
Site 7A	none	0.104	0.101	0.100	0.107	0.103
Site 7B	none	0.008	0.007	0.007	0.007	0.007
Site 7C	none	0.155	0.120	0.128	0.129	0.143
Site 8	none	0.055	0.054	0.052	0.057	0.055
Site 9	none	0.070	0.067	0.072	0.076	0.071
Site 10	none	0.025	0.025	0.025	0.024	0.025

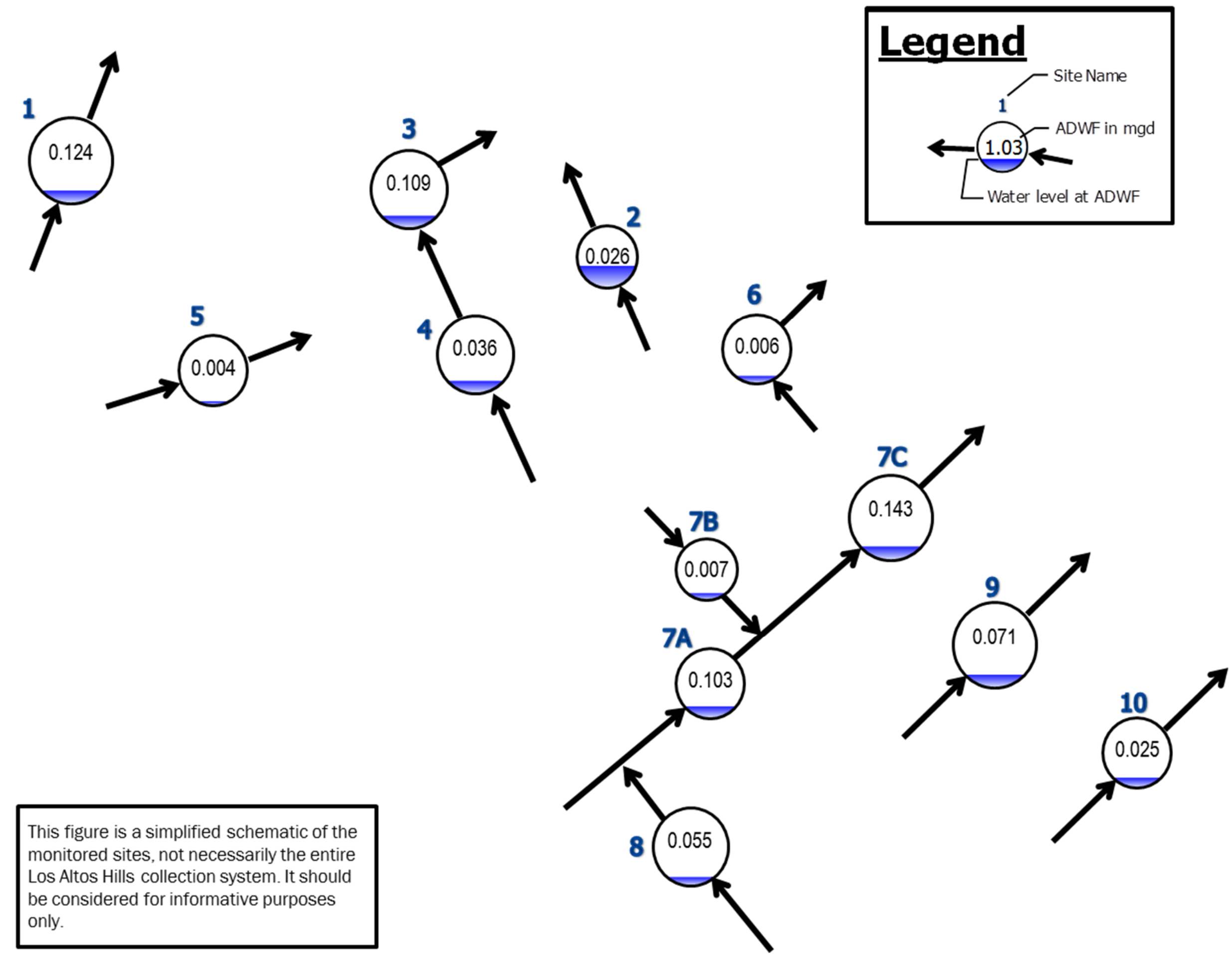


Figure 4-1. Average Dry Weather Flow (Flow Schematic)

4.2 Capacity Analysis: Peaking Factor and d/D Ratio

Peak measured flows and the corresponding flow levels (depths) are important to understand the capacity limitations of a collection system. The peak flows and flow levels reported are from the peak measurements as taken across the entirety of the flow monitoring period. Peak flows and levels may not correspond to a rainfall event.

The following capacity analysis terms are defined as follows:

- **Peaking Factor:** Peaking factor is defined as the peak measured flow divided by the average dry weather flow (ADWF). Peaking factors are influenced by many factors including size and topography of tributary area, proximity to pump stations, and the amount and characteristics of I/I entering the collection system. Flow attenuation and flow restrictions will also affect the peaking factor. A peaking factor threshold value of 3.0 is commonly used for sanitary sewer design of new pipe; however, it is noted that this value is variable and subject to attenuation and the size of the upstream collector area. The Town should follow its own standards and criteria when examining peaking factors.
- **d/D Ratio:** The d/D ratio is the peak measured depth of flow (d) divided by the pipe diameter (D). Standards for d/D ratio vary from agency to agency, but typically range between $d/D \le 0.5$ and $d/D \le 0.75$. The d/D ratio for each site was computed based on the maximum depth of flow for the flow monitoring study.

Table 4-2 summarizes the peak recorded flows, maximum levels, *d/D* ratios, and peaking factors per site during the flow monitoring period. Results of note have been shaded in RED. Capacity analysis data are presented on a site-by-site basis and represents the hydraulic conditions only at the site locations; hydraulic conditions in other areas of the collection system will differ.

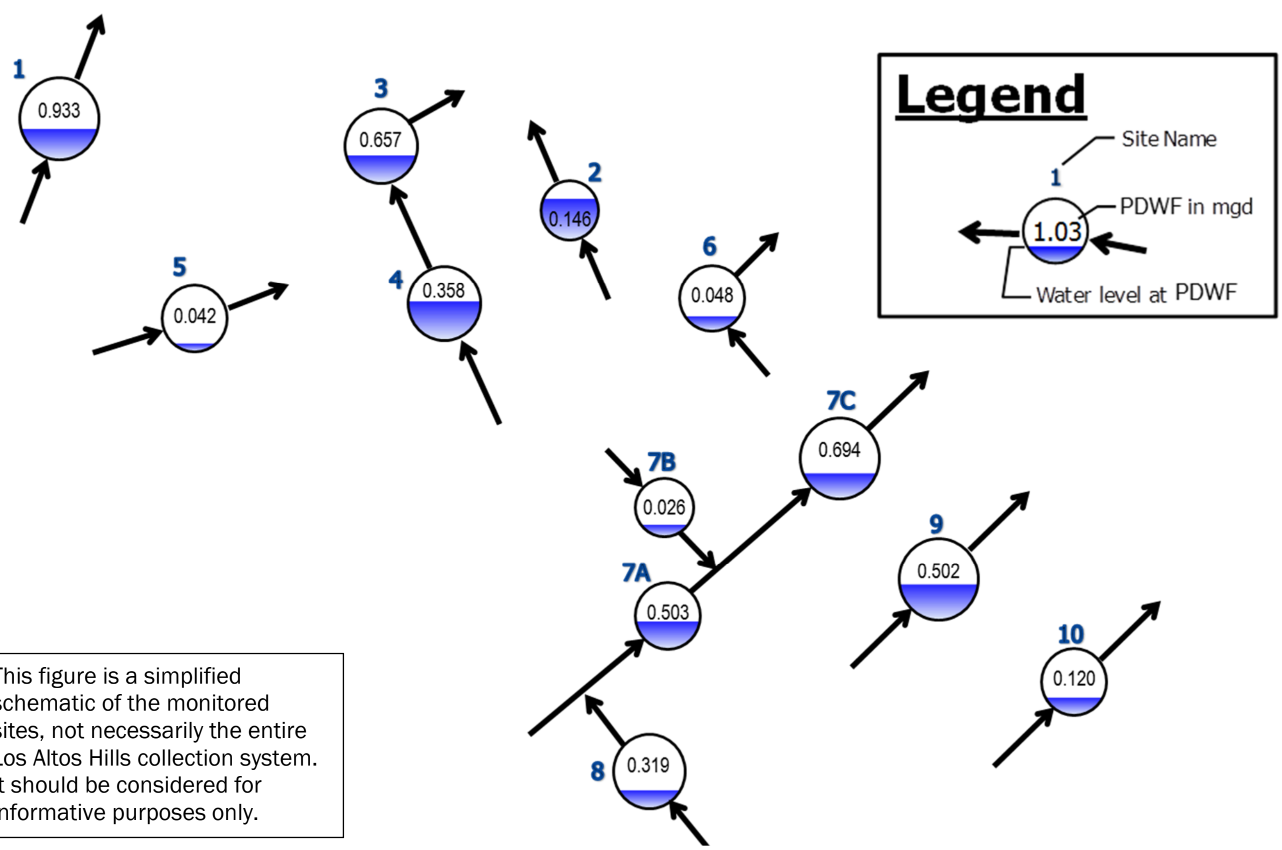
The following capacity analysis results are noted:

- **d/D Ratio:** None of the sites had a maximum *d/D* ratio that exceeded a d/D value of 0.75. None of the sites experienced surcharging during this study.
- **Peaking Factor:** All of the metering sites had peaking factors that exceeded typical design threshold limits for new pipe design. The peak flows for all sites were rainfall-related.

Figure 4-2 shows a schematic diagram of the peak measured flows with peak flow levels. Figure 4-3 and Figure 4-4 show bar graphs of the capacity results.

Table 4-2. Capacity Analysis Summary

Metering Site	ADWF (mgd)	Peak Measured Flow (mgd)	Peaking Factor	Pipe Diameter, *D* (in)	Max Depth, *d* (in)	*d/D* Ratio	Surcharge above Pipe Crown (ft)
Site 1	0.124	0.933	7.5	12	4.56	0.38	-
Site 2	0.026	0.146	5.6	6	4.20	0.70	-
Site 3	0.109	0.657	6.0	10	3.78	0.38	-
Site 4	0.036	0.358	10.0	10	5.28	0.53	-
Site 5	0.004	0.042	9.9	7.75	1.03	0.13	-
Site 6	0.006	0.048	8.1	8	1.81	0.23	-
Site 7A	0.103	0.503	4.9	8	3.32	0.42	-
Site 7B	0.007	0.026	3.6	6	1.24	0.21	-
Site 7C	0.143	0.890	4.0	12	3.85	0.32	-
Site 8	0.055	0.319	5.8	9.5	2.37	0.25	-
Site 9	0.071	0.502	7.1	12	5.31	0.44	-
Site 10	0.025	0.120	4.8	8	2.13	0.27	-



This figure is a simplified schematic of the monitored sites, not necessarily the entire Los Altos Hills collection system. It should be considered for informative purposes only.

Figure 4-2. Peak Measured Flow (Flow Schematic)

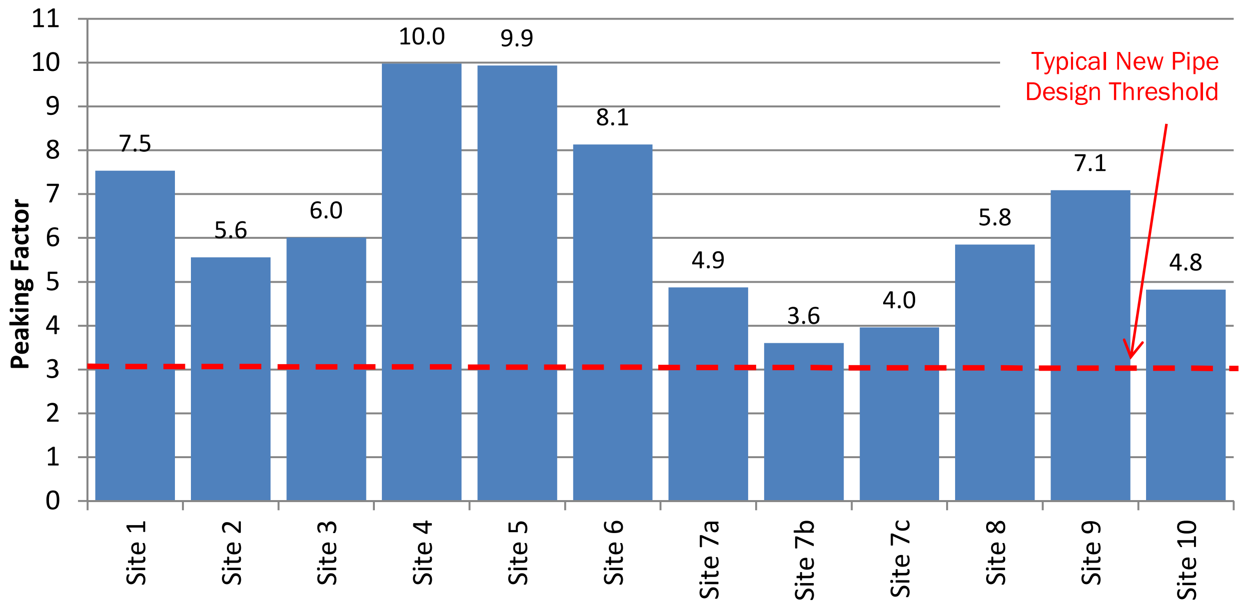


Figure 4-3. Capacity Summary: Peaking Factors

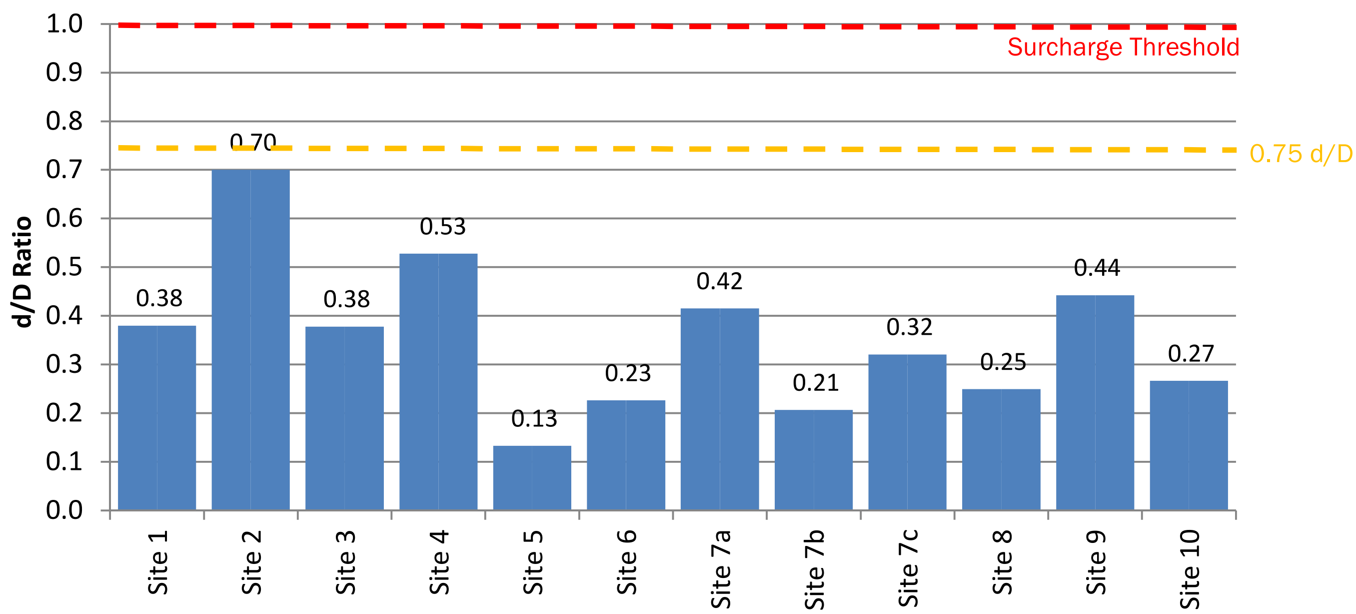


Figure 4-4. Capacity Summary: Max d/D Ratios

5.0 Inflow and Infiltration Results

5.1 Preface

I/I rates were still receding after the March 4 – 8 rainfall event and into the March 10 – 14 rainfall (see Figure 5-1 for further illustration). These two storms were merged into one storm event for purposes of I/I analysis; henceforth named Event 1. Other I/I analysis items noted include the following:

- In the week leading up to Event 1, average daily flows were elevated from baseline levels at Meters 7A, 7C, 8 and 9. V&A established a higher baseline curve for these meters so as to better isolate and evaluate the I/I response for Event 1.
- The elevated RDI levels from the March 4 – 8 rainfall resulted in peak flows at Meters 1, 5, 6, 7B and 10 occurring during the March 10 – 14 rainfall. Peak flows for all other meters occurred during the March 4 – 8 rainfall.
- For all of the metering sites, I/I took five or more days to recede to baseline levels, suggesting generally strong RDI system-wide within the Town collection system.

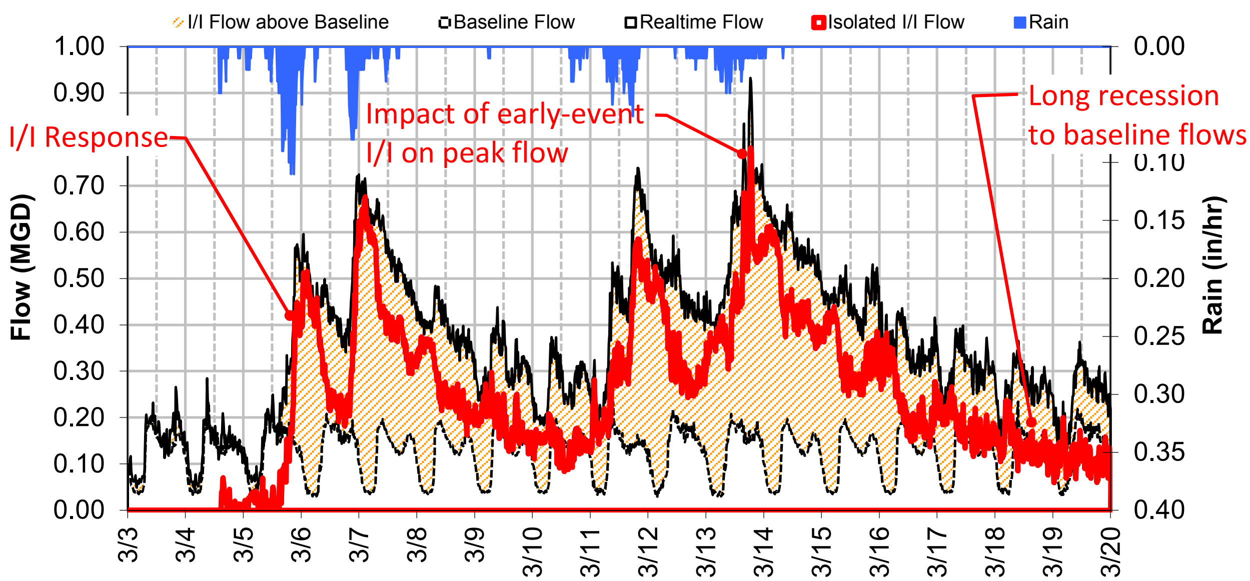


Figure 5-1. I/I Isolation Graph, Site 1

5.2 Inflow Results Summary

Inflow is storm water discharged into the sewer system through direct connections such as downspouts, area drains, cross-connections to catch basins, etc. These sources transport rain water directly into the sewer system and the corresponding flow rates are tied closely to the intensity of the storm. This component of I/I often causes a peak flow problem in the sewer system and often dictates the required capacity of downstream pipes and transport facilities to carry these peak instantaneous flows. Table 5-1 summarizes the peak measured I/I flows and inflow analysis results for Event 1. Figure 5-2 shows a bar graph summary of the inflow analysis.

Table 5-1. Inflow Analysis Summary

Monitoring Site	ADWF (mgd)	Peak I/I Rate (mgd)	Peak I/I per ADWF
Site 1	0.124	0.782	6.32
Site 2	0.026	0.116	4.41
Site 3	0.109	0.561	5.13
Site 4	0.036	0.340	9.47
Site 5	0.004	0.036	8.49
Site 6	0.006	0.041	7.01
Site 7A	0.103	0.370	3.58
Site 7B	0.007	0.018	2.39
Site 7C	0.143	0.628	4.40
Site 8	0.055	0.217	3.97
Site 9	0.071	0.410	5.78
Site 10	0.025	0.085	3.41

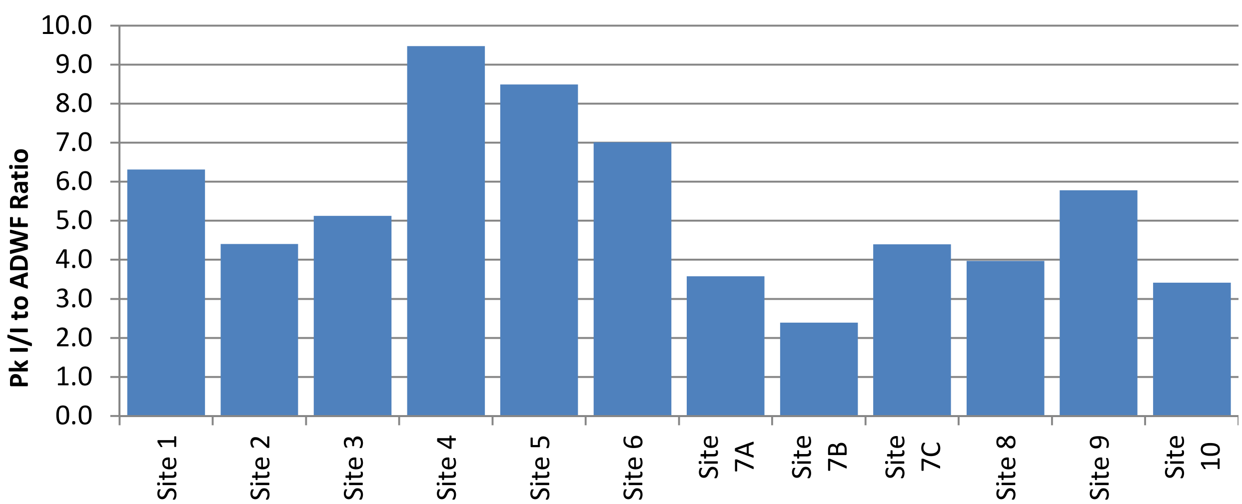


Figure 5-2. Bar Graph: Inflow Analysis Summary

5.3 RDI Results Summary

Infiltration is defined as water entering the sanitary sewer system through defects in pipes, pipe joints, and manhole walls, which may include cracks, offset joints, root intrusion points, and broken pipes. Increased flows into the sanitary sewer system are usually tied to groundwater levels and soil saturation levels. Infiltration sources transport rain water into the system *indirectly*; flow levels in the sanitary system increase gradually, are typically sustained for a period after rainfall has stopped, and then gradually drop off as soils become less saturated and as groundwater levels recede to normal. Infiltration typically creates long-term annual volumetric problems. The major impact is the cost of pumping and treating the additional volume of water, and of paying for treatment (for municipalities that are billed strictly on flow volume).

For this study, the RDI rate used for comparative analysis was measured as the average I/I rate from March 15 at 12:00 noon to March 17 at 12:00 noon (a little more than 24 hours after the conclusion of the March 10 - 14 rain event). Figure 5-3 illustrates this for Site 4.

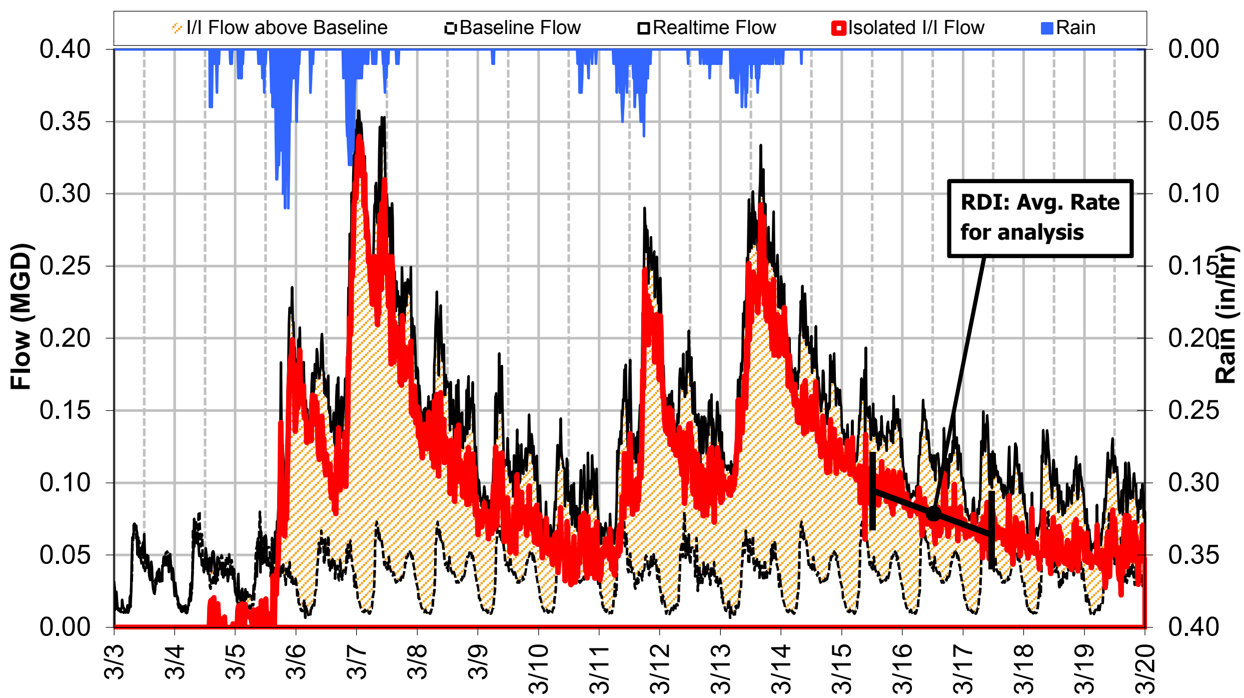


Figure 5-3. RDI Measurement, Site 4

Table 5-2 summarizes the calculated RDI flow rates for Event 1. Figure 5-4 shows a bar graph summary.

Table 5-2. Basins RDI Analysis Summary

Metering Basin	ADWF (mgd)	RDI Rate (mgd)	RDI per ADWF
Site 1	0.124	0.244	2.0
Site 2	0.026	0.016	0.6
Site 3	0.109	0.132	1.2
Site 4	0.036	0.080	2.2
Site 5	0.004	0.010	2.4
Site 6	0.006	0.015	2.6
Site 7A	0.103	0.063	0.6
Site 7B	0.007	0.000	0.0
Site 7C	0.143	0.113	0.8
Site 8	0.055	0.035	0.6
Site 9	0.071	0.072	1.0
Site 10	0.025	0.025	1.0

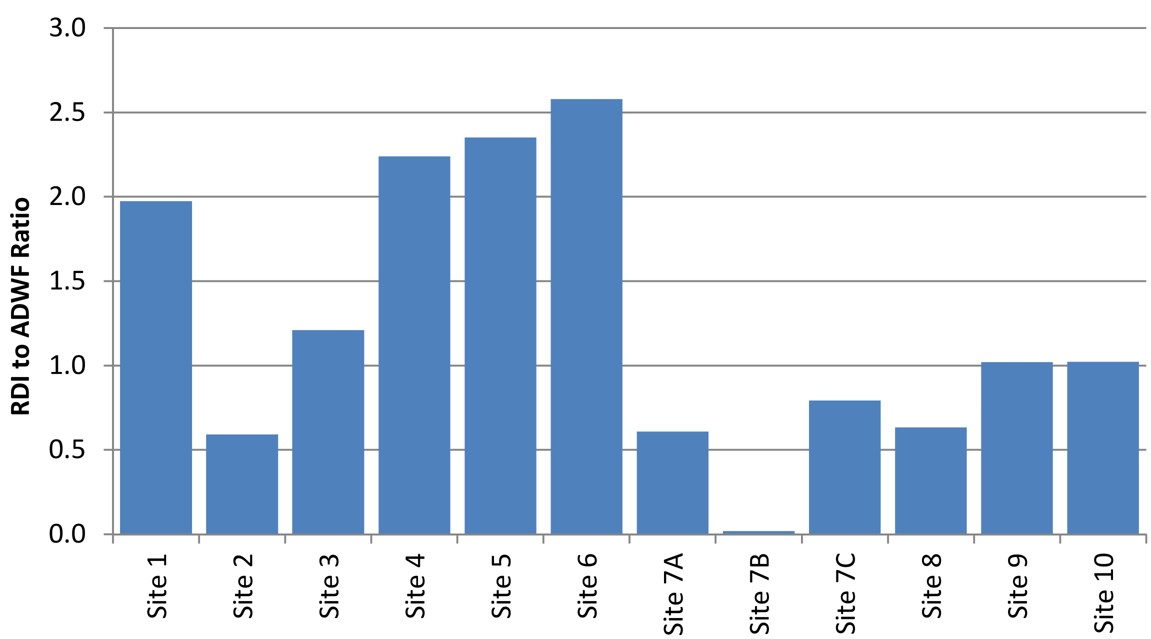


Figure 5-4. Bar Graphs: RDI Analysis Summary

5.4 Groundwater Infiltration Results Summary

Dry weather (ADWF) flow can be expected to have a predictable diurnal flow pattern. While each site is unique, experience has shown that, given a reasonable volume of flow and typical loading conditions, the daily flows fall into a predictable range when compared to the daily average flow. If a site has a large percentage of groundwater infiltration occurring during the periods of dry weather flow measurement, the amplitudes of the peak and low flows will be dampened[6]. Figure 5-5 shows a sample of two flow monitoring sites, both with nearly the same average daily flow, but with considerably different peak and low flows. In this *sample* case, Site B1 may have a considerable volume of groundwater infiltration.

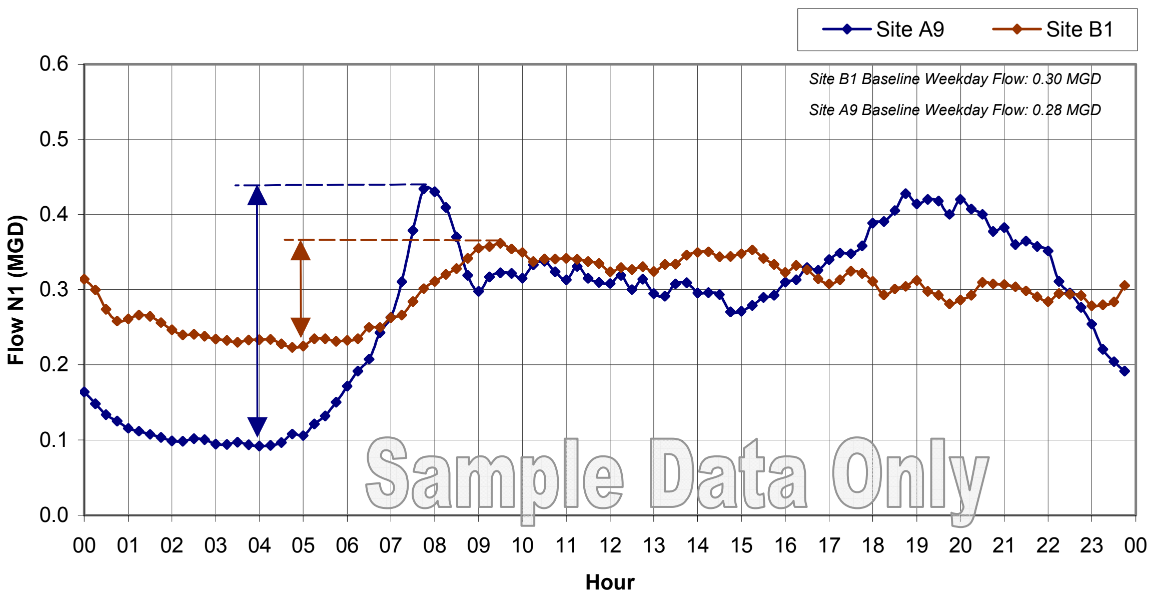


Figure 5-5. Groundwater Infiltration Sample Figure

It can be useful to compare the low-to-ADWF flow ratios for the flow metering sites. A site with abnormal ratios, and with no other reasons to suspect abnormal flow patterns (such as proximity to a pump station, treatment facilities, etc.), has a possibility of higher levels of groundwater infiltration in comparison to the rest of the collection system.

Figure 5-6 plots the low-to-ADWF flow ratios against the ADWF flows for the sites monitored during this study. The dotted line shows "typical" low-to-ADWF ratios per the Water Environment Federation (WEF)[7].

[6] In an extreme case, perhaps 0.2 mgd of ADWF flow and 2.0 mgd of groundwater infiltration, the peaks and lows would be barely recognizable; the ADWF flow would be nearly a straight line.
[7] WEF Manual of Practice No. 9, "Design and Construction of Sanitary and Storm Sewers."

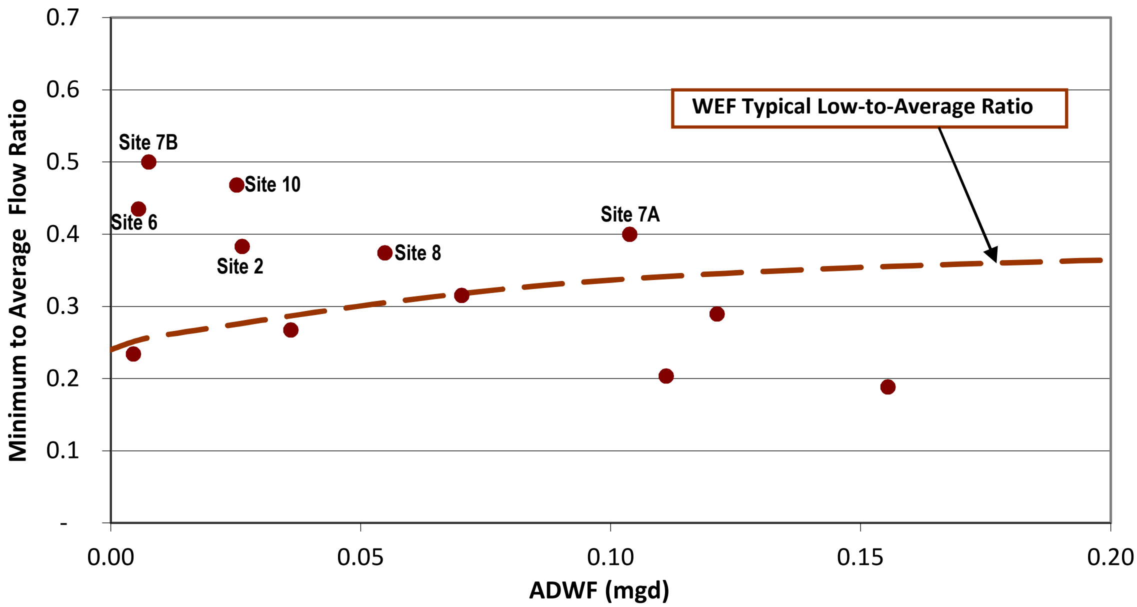


Figure 5-6. Comparison of Meter Basin GWI to Typical WEF Ratios

The graph suggests that GWI in the basins upstream from Sites 2, 6, 7A, 7B, 8 and 10 is above typical groundwater infiltration standards (as set forth by WEF). Table 5-3 summarizes excess GWI that, if removed, would bring the above sites to within typical WEF Low-to-Average Ratios.

Table 5-3. Excess GWI per WEF

Metering Site	Excess GWI (mgd)	Excess GWI (gpm)
Site 2	0.004	2.5
Site 6	0.001	1.0
Site 7A	0.010	7.2
Site 7B	0.003	1.8
Site 8	0.005	3.5
Site 10	0.007	4.6

It is noted that the rates of excess GWI are low.

5.5 Combined I/I Results Summary

Combined I/I analysis considers the totalized volume (in gallons) of both inflow and rainfall-dependent infiltration over the course of a storm event. Table 5-4 summarizes the combined I/I flow results for Event 1 . Figure 5-7 shows a bar graph summary of the combined I/I analysis.

Table 5-4. Basins Combined I/I Analysis Summary

Metering Basin	ADWF (mgd)	Combined I/I (gallons) [A]	Combined I/I per ADWF
Site 1	0.124	4,103,000	2.0
Site 2	0.026	348,000	0.8
Site 3	0.109	2,251,000	1.2
Site 4	0.036	1,581,000	2.6
Site 5	0.004	127,000	1.8
Site 6	0.006	192,000	1.9
Site 7A	0.103	1,102,000	0.6
Site 7B	0.007	34,000	0.3
Site 7C	0.143	2,148,000	0.9
Site 8	0.055	634,000	0.7
Site 9	0.071	1,281,000	1.1
Site 10	0.025	362,000	0.9

[A] Measured over a 16-day storm period.

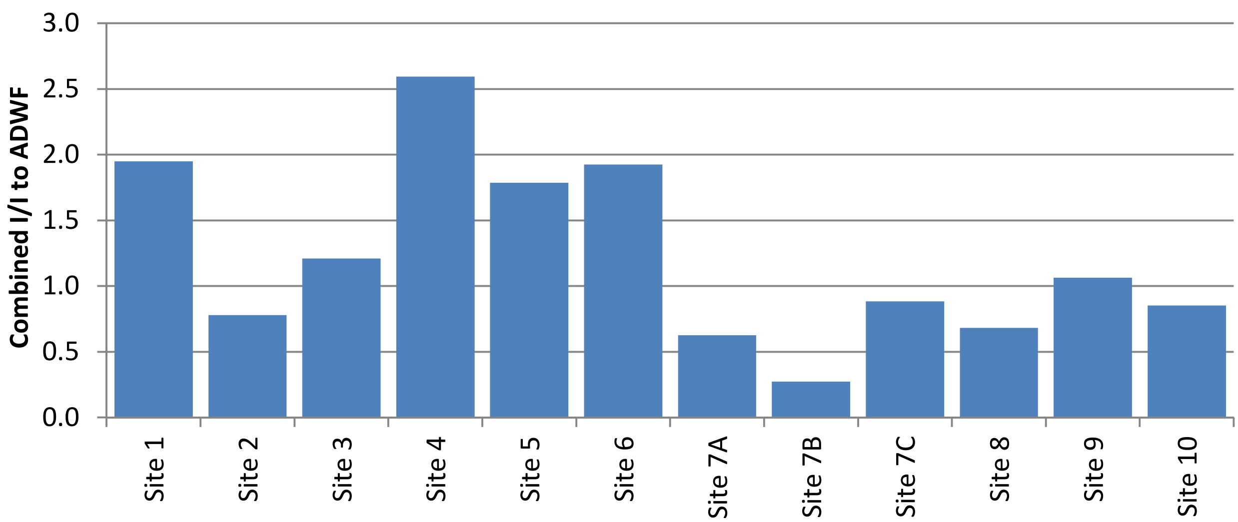


Figure 5-7. Bar Graphs: Combined I/I Analysis Summary

6.0 I/I INVESTIGATION AND REDUCTION

For this study, it is not V&A's intent to rank or otherwise suggest the next course of action to be taken in regards to any CIP decisions regarding collection system capacity or RDI/I mitigation. The Town master planning consultant will determine the effect of the rainfall intensity on the RDI/I response within the collection system. V&A will not make any specific recommendations in this final report. These data and the interpretation of these data should be used per the discretion of the Town Engineer. V&A presents the following general I/I reduction guidelines for I/I mitigation and reduction:

1. **Determine I/I Reduction Program:** The Town should examine its I/I reduction needs to determine a future I/I reduction program.
   a. If peak flows, sanitary sewer overflows, and pipeline capacity issues are of greater concern, then priority can be given to investigate and reduce sources of inflow within the basins with the greatest inflow problems.
   b. If total infiltration and general pipeline deterioration are of greater concern, then the program can be weighted to investigate and reduce sources of infiltration within the basins with the greatest infiltration problems.
2. **I/I Investigation Methods:** Potential I/I investigation methods include the following:
   a. Smoke testing
   b. Mini-basin flow monitoring
   c. Nighttime reconnaissance work to (1) investigate and determine direct point sources of inflow and (2) determine the areas and pipe reaches responsible for high levels of infiltration contribution.
3. **I/I Reduction Cost-Effectiveness Analysis:** The Town should conduct a study to determine which is more cost-effective: (1) locating the sources of inflow and infiltration and systematically rehabilitating or replacing the faulty pipelines or (2) continued treatment of the additional rainfall-dependent I/I flow.

APPENDIX A. FLOW MONITORING SITES: DATA, GRAPHS, INFORMATION